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Light Gluinos at LEP

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Abstract

We study the production and decay of light gluinos in e^+e^- collisions. We suggest a signature which suffers little from backgrounds and argue that the light gluino window can already be closed with the existing LEP data, provided the gluino lifetime is such that it decays within the detectors.

1 Introduction

Historically seen, there are three kinds of elementary particles: those whose discovery was unexpected and revolutioned our perception of the world, like the neutron or the strange quark; those whose existence had been foreseen and whose discovery confirmed the speculations of a brilliant mind, like the positron or the electroweak gauge bosons; but there are also those which were predicted and have never been found. Very often it is difficult to preclude the existence of the latter on the sole basis that they have not shown up yet in experiments. Indeed, generally the models which predict their existence can be adapted in such a way that their couplings to ordinary matter becomes so low that even the highest precision measurements would be unable to detect their presence, or that the mass of these particles becomes so high that even the highest energy experiments would not produce them. This adaptation of the models often goes with a dramatic decrease in the esthetic value of the considerations which, no doubt, motivated their elaboration. In some cases, a particle “soon-to-be-discovered” is even demoted to an “invisible” status.

There is, however, an exception to this rule: the light gluino. The gluino is predicted by the theory of supersymmetry to be the spin 1/2 partner of the gluon. Like the gluon, it is its own anti-particle, hence a Majorana spinor, and it couples to ordinary matter with the same strength as a gluon. Strangely enough, in spite of its strong interactions and substantial efforts from both theorists and experimentalists, it has not yet been possible to rule out the existence of a gluino weighing less than 5 GeV [1, 2, 3, 4, 5]! A number of studies has been devoted to exclude at least some windows within this impertinent mass gap, but none of them has been absolutely conclusive.

It is the purpose of this letter to attempt to settle the ongoing controversy about the existence of this light gluino. For this we compute the production rate of gluinos in e^+e^- collisions and study their decay signature. It turns out that the background arising from the standard model and detector inefficiencies can be virtually eliminated with b -tagging. We confined this study to the case of LEP, because of the high cross sections obtained on the Z^0 peak.

2 Gluino Production

The lowest order cross section for producing gluinos in e^+e^- collisions can be computed from the Feynman diagrams of Fig. 1. For massless quarks it can be

written

$$\sigma_{\tilde{g}} = \frac{2N_c\alpha^2\alpha_s^2}{3\pi s} \sum_f \Gamma_f \int_{4m_{\tilde{g}}^2}^s dm^2 \sqrt{1 - \frac{4m_{\tilde{g}}^2}{m^2}} \left(1 + \frac{2m_{\tilde{g}}^2}{m^2}\right) \frac{1}{m^2} T\left(\frac{m^2}{s}\right), \quad (1)$$

where $N_c = 3$ is the number of colours, α is the fine structure constant, α_s is the strong coupling constant and $m_{\tilde{g}}$ is the gluino mass. The scaled γ - Z^0 propagator squared Γ_f is summed over all active quark flavours f . It is given by

$$\Gamma_f = Q_f^2 - v_e v_f Q_f \frac{s(s - m_Z^2)}{(s - m_Z^2)^2 + m_Z^2 \Gamma_Z^2} + (v_e^2 + a_e^2)(v_f^2 + a_f^2) \frac{s^2}{(s - m_Z^2)^2 + m_Z^2 \Gamma_Z^2} \quad (2)$$

where v_e , a_e , v_f and a_f are the electron's and quark's vector and axial vector couplings to the Z^0 boson and Q_f is the quark's charge. The integral in Eq. (1) is over the gluon virtuality and the function T is given by

$$T(x) = \frac{2}{3} \left\{ (1+x)^2 \left[\ln^2(x+1/x+2) - \pi^2/3 + \Sigma(x) \right] + (3+4x+3x^2) \ln x + 5(1-x^2) \right\}, \quad (3)$$

where

$$\begin{cases} \Sigma(x) = \sum_{n=1}^{\infty} c_n \left(\frac{4}{x+1/x+2} \right)^n \\ c_n = c_{n-1} \frac{2n-1}{2n-2} \left(\frac{n-1}{n} \right)^3 \\ c_1 = 1 \end{cases} \Rightarrow \begin{cases} \Sigma(0) = 0 \\ \Sigma(1) = \pi^2/3 - \ln^2 4 \end{cases}$$

For low gluino masses the gluon virtuality m^2 in Eq. (1) is allowed to approach zero. In this limit the function T takes the asymptotic divergent form [6]

$$T(\epsilon) = \frac{2}{3} \ln^2 \epsilon + 2 \ln \epsilon + \frac{10}{3} - \frac{2}{9} \pi^2 \quad \text{for} \quad \epsilon = 0. \quad (4)$$

This expression clearly displays the double and single logarithmic divergences which appear when integrating over the infra-red and collinear regions of phase space. These are approached only when the gluon virtuality in Eq. (1) can be small, *i.e.* when the gluino mass is small. The cross section obtained from Eq. (1) is thus not trustworthy when the gluino is too light. A convenient method to counter this deficiency is to avoid altogether the infra-red and collinear regions of phase space where the cross section is unphysically large. The easiest kinematical cut which comes to mind is to impose a lower bound M on the invariant mass of the gluino pair. This is done in Eq. (1) by replacing the lower integration limit $4m_{\tilde{g}}^2$ by M^2 . This way, the virtuality of the gluon is never allowed to come close to zero and the doubtful regions of phase space are not approached.

Of course, one might wonder how to implement this cut experimentally. Indeed, the produced gluinos, and partons in general, radiate soft and collinear gluons which themselves radiate even softer gluons. This cascade develops until the relative transverse momentum of the partons reaches the hadronization scale (~ 1 GeV) and a jet is born. What happens then can only be simulated with models (*e.g.* string or cluster hadronization [7]). Something seems to be guaranteed, however: heavy quark jets contain a heavy hadron, light quark and gluon jets contain only light hadrons, and gluino jets contain a glueballino. This makes b -tagging an invaluable tool for recognizing quark jets as such. With this option the kinematical cut can be unambiguously implemented on the overall invariant mass of the remaining jet or jets, those which might have been initiated by a pair of gluinos.

Note that Eq. (1) also gives the rate at which two quark pairs $q\bar{q}q'\bar{q}'$ are produced, if the the colour factor N_c is replaced by the number of active flavours N_f .

3 Gluino Decay

We shall assume in the following that R-parity remains unbroken and that the lightest supersymmetric particle is a neutralino. If this is the case a light gluino decays predominantly via the exchange of a squark into a quark-antiquark pair accompanied by the lightest neutralino, which remains undetected. Higher order decay mechanism can compete only for very contrived values of the supersymmetry parameters [8] and we therefore do not consider them here.

According to this scenario, if the gluino is very light, the lightest neutralino has to be almost massless. This can only be the case if either of the supersymmetry parameters μ or M_2 is small. In turn, $\tan\beta$ can then not be much larger than one, in order to accomodate the LEP bounds on the chargino mass. If the light mass of the neutralino is achieved by a low value of μ , its main component is a Higgsino. In this case, the gluino will eventually decay, but its lifetime is too long for this to happen within a detector. On the other hand, if M_2 is small, the lightest neutralino is dominantly a photino and the lifetime of the gluino is of the order of a weak decay lifetime. We therefore assume in the following that

$$M_2 = 0 \quad \Rightarrow \quad \begin{cases} \tilde{\chi}_1^0 = \tilde{\gamma} \\ m_{\tilde{\gamma}} = 0 \end{cases} . \quad (5)$$

For N_f flavours of massless quarks and heavy squarks, the decay width of a free gluino is [9]

$$\Gamma = \frac{\alpha\alpha_s}{48\pi} \sum_f^{N_f} Q_f^2 \frac{m_{\tilde{g}}^5}{m_{\tilde{q}}^4} , \quad (6)$$

where α is the fine structure constant, α_s is the strong coupling constant, Q_f is the quark charge and $m_{\tilde{g}}$ and $m_{\tilde{q}}$ are the gluino and squark masses. The invariant mass M_h of the quark pair emerging from the decay of the gluino is distributed according to

$$\frac{1}{\Gamma} \frac{d\Gamma}{dM_h} = \frac{4}{m_{\tilde{g}}^8} M_h \left(m_{\tilde{g}}^6 - 3m_{\tilde{g}}^2 M_h^4 + 2M_h^6 \right). \quad (7)$$

All this was said for a free gluino. In reality a gluino would emerge at the end of a hadronization process in a colour blanched bound state, most probably a glueballino $\tilde{G} = g\tilde{g}$. The decay of this gluon-gluino meson is dictated by the decay mechanism of the gluino. It consists of a secondary vertex within a jet, to which no charged track is leading. Off this vertex, only hadrons emerge and their invariant mass is continuously distributed over the full range $[0, m_{\tilde{G}}]$ according to Eq. (7). Actually, bound state effects are expected to harden this free gluino spectrum. However, since this shift towards higher invariant masses amounts to only a small correction in the present analysis, we assume here the validity of Eq. (7) (with $m_{\tilde{G}}$ replacing $m_{\tilde{g}}$) also for the hadron spectrum of a glueballino. Only the long-lived neutral hadrons (K^0 , Λ , D^0 , B^0 , ...) have similar signatures, but their decay hadrons emerge with sharply peaked invariant masses.

At this stage the lifetime of a glueballino can only be estimated. According to Ref. [9] it is approximated by the same formula (6) as for the decay of a free gluino, replacing the gluino mass by an effective glueballino mass $m_{\tilde{G}}^* \approx .75m_{\tilde{G}}$. But the glueballino mass itself is also just a guess. Nevertheless, even for a massless gluino it is unlikely to be smaller than 1 GeV, and for a heavier gluino, it will probably be close to the mass of the gluino itself. For our purposes we assume that the effective mass to be used in Eq. (6) is well approximated by the mass of the gluino itself, but cannot be less than .75 GeV. The range of values which the squark and effective glueballino masses can then take for the glueballino decay to be detectable within a typical time projection chamber ($L \lesssim 2\text{m}$) or vertex detector ($L \gtrsim 2\text{mm}$) is shown in Fig. 2. This fills a large portion of the parameter space left by some other conclusive studies [1] or applicability arguments: $74 \text{ GeV} < m_{\tilde{q}} < 2 \text{ TeV}$ and $.75 \text{ GeV} < m_{\tilde{G}}^* < 4 \text{ GeV}$. The latter bounds should correspond closely to $0 \text{ GeV} < m_{\tilde{g}}^* < 4 \text{ GeV}$. The kink at $m_{\tilde{G}}^* = 2.7 \text{ GeV}$ is due to the opening of the charmed decay channel.

4 Signal and Backgrounds

The procedure we propose for discriminating a light gluino in e^+e^- collisions consists of the following selection criteria:

- Events with three or more jets.
- Two of these jets contain clearly identified b quarks.
- The overall invariant mass of the remaining jet(s) exceeds a certain lower bound M .
- These remaining jet(s) contain two secondary vertices with only hadrons emerging and which are not initiated by a charged track.
- The invariant masses of the hadrons leaving these secondary vertices do not overlap with the masses of the long-lived neutral hadrons¹: K^0 , D^0 , B^0 and Λ .

In order to implement the first two requirements one should, in principle, define what is a jet. Typically, this can be done by invoking a jet-finding procedure, like the Durham [10] or the Jade [11] algorithm. A more complete study including a full detector simulation, should indeed include these refinements. Here, however, we do not incorporate them, because they cannot be applied to our nearly integrated cross section (1) and do not modify our conclusions.

In principle, there is no standard model background for events satisfying the five requirements listed above. In practice, however, there are cracks in the detectors, through which a hadron can escape and falsify the invariant mass measurement of a long-lived hadron. Moreover, some of these hadrons can also decay semi-leptonically, in which case the invariant mass measurement can also be falsified if an electron is mistaken for a pion.

Obviously, these effects can only be accurately estimated with a complete and dedicated detector simulation. Still, an order of magnitude calculation reveals that these backgrounds are negligible. Indeed, if the selection criteria above are implemented, the heavy hadrons which are at the origin of the background can only be produced in 4-quark events² of the type $b\bar{b}q\bar{q}$. The rate of these events is $\frac{N_f}{N_c}\sigma_{\bar{g}}$ (see Eq. (1), where the only active flavour is $f = b$) and the background cross section is thus

$$\begin{aligned} \sigma_{\text{SM}} = \sigma_{\bar{g}} \frac{N_f}{N_c} \eta^2 & \left[P(\Lambda) BR(\Lambda \rightarrow e^\pm \nu + \text{hadrons}) \right. \\ & + P(D^0) BR(D^0 \rightarrow e^\pm \nu + \text{hadrons}) \\ & \left. + P(B^0) BR(B^0 \rightarrow e^\pm \nu + \text{hadrons}) \right]^2, \quad (8) \end{aligned}$$

¹ There are more long-lived baryons, but their occurrence is so rare that we can safely ignore them here.

² The production of heavy flavours is very much suppressed in gluon jets. Therefore $b\bar{b}g$ or $b\bar{b}gg$ events cannot satisfy the selection criteria.

where η is the probability to misidentify electrons. The branching ratios BR for electronic decays of the Λ , D^0 and B^0 are respectively .083%, 7.7% and 12.1% [1] while the probabilities P of finding these hadrons in a quark jet are of the order of 30% or less. The K^0 plays no role here, because the K_L^0 decays far outside the detectors and the K_S^0 has no semi-leptonic decay. Typically, LEP detectors can discriminate electrons and pions better than to 1% ($\eta = 10^{-2}$). The ratio $\sigma_{\tilde{g}}/\sigma_{\text{SM}}$ is thus so large that we can safely ignore the backgrounds caused by inefficiencies in the electron identification. The same argument holds for the backgrounds due to imperfect detector hermeticities.

The gluino cross section which is obtained when implementing our selection criteria is displayed in Fig. 3 as a function of the gluino mass for several choices of the minimum invariant mass M of the gluino pair. To obtain this result, we assumed an invariant mass resolution of 100 MeV and chose the b -tagging procedure to be 50% efficient. For 100 pb^{-1} of integrated luminosity (which should have been accumulated at LEP1 with b -tagging by now), even a 20 GeV gluino (which has already been clearly ruled out by previous experiments) would provide more than 10 events which cannot be explained within the framework of the standard model! In turn, a light gluino of less than 5 GeV would generate several thousands of such events.

5 Conclusions

We have studied the production and decay of light gluinos at LEP and suggested a signature with no or negligible backgrounds from the standard model and detector inefficiencies. It appears that the existence of a light gluino can easily be confirmed or ruled out with the data already accumulated at LEP, provided the glueballino $g\tilde{g}$ bound state decays neither outside the detectors nor too close to the primary vertex. The corresponding domain of observability in the space of the glueballino and squark masses is shown in Fig. 2, assuming the photino achieves its “lightest supersymmetric particle” status with $M_2 \approx 0$ within the framework of the minimal supersymmetric standard model.

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Figure 1: Lowest order Feynman diagrams contributing to gluino production in e^+e^- collisions.

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Figure 2: Curves corresponding to the average distances of 2 mm and 2 m traveled by a glueballino in the still allowed space of the glueballino effective mass and the squark mass. The darkened area can be explored by the method advocated here.

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Figure 3: LEP cross sections for the gluino signal described in the text, as a function of the gluino mass. The incidence of different choices for the lower bound imposed on the invariant mass of the non- b quark jets is also shown.